INVESTIGATION OF HEAT AFFECTED ZONE AND CIRCULARITY ON LASER CUTTING USING REGRESSION ANALYSIS

Himanshu B. Joshi[1], Prof. Kiran C Patel[2]
[2]Assistant Professor
[1]M.E (Pursuing in Production Engineering), [2]M.E (Advance Manufacturing Technics)
S P B Patel Engineering College, Linch, Mehsana

ABSTRACT: Selection of optimal cutting parameter settings for obtaining high cut quality in Nd:YAG laser cutting process is of great importance. Among various analytical and experimental optimization methods, the application of Taguchi and regression analysis is one of the most commonly used for laser cutting process optimization. In this research an approach for optimization of Nd:YAG laser cutting process using Taguchi and regression analysis is presented. The Objective is to determine the near optimal laser cutting parameter values in order to ensure robust condition for maximize the Material Removal Rate and Circularity and minimize the Heat Affected Zone. Four cutting parameters, the Cutting speed (1200, 1500, 1800, 2100, 2400 mm/min), the Laser Power (150, 200, 250, 300, 350 W), Assist Gas Pressure (2, 3, 4, 5, 6 bar), and the Standoff Distance (0.5,0.8,1,1.2,1.5 mm) will used in the experiment. To obtain near optimal cutting parameters settings.
Keywords: Laser cutting, Material Removal Rate, Heat Affected Zone, Circularity, INCONEL625.

I. INTRODUCTION

The acronym LASER, constructed from Light Amplification by Stimulated Emission of Radiation, has become so common and popular in every day life that it is now referred to as laser. Fundamental theories of lasers, their historical development from milli watts to peta watts in terms of power, operation principles, beam characteristics, and applications of laser have been the subject of several books Introduction of lasers, types of laser systems and their operating principles, methods of generating extreme ultraviolet/vacuum ultraviolet (EUV/VUV) laser lights, properties of laser radiation, and modification in basic structure of lasers.

1.1 History of Laser[13]

The first gas laser was developed in 1961 by A. Javan, W. Bennet, and D. Harriott of Bell Laboratories, using a mixture of helium and neon gases. At the same laboratories, L. F Johnson and K. Nassau demonstrated the first neodymium laser, which has since become one of the most reliable lasers available. This was followed in 1962 by the first semiconductor laser, demonstrated by R. Hall at the General Electric Research Laboratories. In 1963, C. K. N. Patel of Bell Laboratories discovered the infrared carbon dioxide laser, which is one of the most efficient and powerful lasers available today. Later that same year, E. Bell of Spectra Physics discovered the first ion laser, in mercury vapour. In 1964 W.Bridges of Hughes Research Laboratories discovered the argon ion laser, and in 1966 W. Silfvast, G.R. Fowles, and B. D. Hopkins produced the first blue helium-cadmium metal vapour laser. During that same year, P. P. Sorokin and J. R. Lankard of the IBM Research Laboratories developed the first liquid laser using an organic dye dissolved in a solvent, thereby leading to the development of broadly tunable lasers. Beside, W. Walter and co-workers at TRG reported the first copper vapour laser. In 1961, Fox and Li described the existence of resonant transverse modes in a laser cavity. That same year, Boyd and Gordon obtained solutions of the wave equation for confocal resonator modes. Unstable resonators were demonstrated in 1969 by Krupke and Sooy and were described theoretically by Siegman. Q-switching was first obtained by McClung and Hellwarth in 1962 and described later by Wagner and Lengyel. The first mode-locking was obtained by Hargrove, Fork, and Pollack in l964. Since then, many special cavity arrangements, feedback schemes, and other devices have been developed to improve the control, operation, and reliability of lasers. A laser beam is created by the introduction of gas and electric current in a sealed chamber. As the electricity breaks down the gas energy is released and it resonates between the mirrors within the chamber. While it resonates intensity of the energy increases and of its optimum is released through a partially transmissive mirror. The beam is then directed to a focusing lens and is further intensified. At this point the laser beam becomes a usable cutting device. Some advantages of cutting with lasers include the ability to cut incredible complex shapes without tooling or set-ups. This makes it perfect to produce a huge variety of different products. Laser beam cutting systems cut quickly and very accurately for a wide range of materials. In general, for steel, laser beam cutting process lies between cutting with wire EDM (which is more precise but slower) and plasma (which is less precise but faster). It goes well beyond the range of other methods as well as can cut anything within certain thicknesses. The word “Laser” stands for “Light Amplification by Stimulated Emission of Radiation”. Laser cutting machines are more powerful and also easier to operate. Programmed lasers are easier than ever. Modern machines are capable to adjust their parameters to cut a given material of a defined thickness and also to adjust it selves to machine for a difficult geometry. Nowadays, laser programming systems have comprehensive material databases for carbon steel, stainless, and aluminum, which helps a new user to begin the production rapidly with minimal training. When given a clear geometry file and the definition of the material type, the computer will generate machine codes automatically.

Lasers no longer require daily adjustments to set their cutting parameters. A job that runs one day can run just next day, a week, or a month later. The scientific image of lasers can be a bit daunting. Some working knowledge of computers, basic math skills, a little bit of logical, and some training by the machine manufacturer are needed. Laser cutting operation is both dynamic and stochastic process for the laser operators to handle it easily, with fluctuations in absorbed power, material composition and optical integrity. It is beneficial to develop steady-state modeling for obtaining the approximate order of magnitudes for various parameters. But there are clearly limitations when such models are used as controls. Consequently, an experimental investigation into the laser cut quality is essential to predict the actual control parameters.

Almost all engineering materials are machine by laser beam cutting process. However, material properties such as absorption to electromagnetic wave length, thermal conductivity and electrical conductivity, melting point and surface conditions govern the selection of laser and optics systems. Weather in the Asian countries has higher humidity and hence stainless steel replaces mild steel which is used as a common building and decorative material. Stainless steel cannot be cut using traditional oxy-fuel cutting equipment because of its higher melting point and due to the viscosity of the oxide formed.

1.2 Basic Construction and Principle of Laser[13]

Basically, every laser system essentially has an active/gain medium, placed between a pair of optically parallel and highly reflecting mirrors with one of them partially transmitting, and an energy source to pump active medium. The gain media may be solid, liquid, or gas and have the property to amplify the amplitude of the light wave passing through it by stimulated emission, while pumping may be electrical or optical. The gain medium used to place between pair of mirrors in such a way that light oscillating between mirrors passes every time through the gain medium and after attaining considerable amplification emits through the transmitting mirror. Let us consider an active medium of atoms having only two energy levels: excited level E2 and ground level E1. If atoms in the ground state, E1, are excited to the upper state, E2, by means of any pumping mechanism (optical, electrical discharge, passing current, or electron bombardment), then just after few nanoseconds of their excitation, atoms return to the ground state emitting photons of energy $h\nu = E2 - E1$. According to Einstein's 1917 theory, emission process may occur in two different ways, either it may induced by photon or it may occur spontaneously. The former case is termed as stimulated emission, while the latter is known as spontaneous emission. Photons emitted by stimulated emission have the same frequency, phase, and state of polarization as the stimulating photon; therefore they add to the wave of stimulating photon on a constructive basis, thereby increasing its amplitude to make lasing. At thermal equilibrium, the probability of stimulated emission is much lower than that of spontaneous emission (1 : 1033), therefore most of the conventional light sources are incoherent, and only lasing is possible in the conditions other than the thermal equilibrium.

1.3 Einstein Relations and Gain Coefficient[13]

Consider an assembly of N1 and N2 atoms per unit volume with energies E1 and E2(E2 >E1) is irradiated with photons of density $\rho\nu = N\ h\upsilon$, where [N] is the number of photons of frequency ν per unit volume. Then the stimulated absorption and stimulated emission rates may be written as N1ρνB12 and N2ρνB21 respectively, where B12 and B21 are constants for up and downward transitions, respectively, between a given pair of energy levels. Rate of spontaneous transition depends on the average lifetime, τ21, of atoms in the excited state and is given by N2A21, where A21 is a constant. Constants B12, B21, and A21 are known as Einstein coefficients. Employing the condition of thermal equilibrium in the ensemble, Boltzmann statistics of atomic distribution, and Planck's law of blackbody radiation, it is easy to find out B12 = B21, A21 = B21(8πhν3/c3), known as Einstein relations, and ratio, $R = \exp(h\nu/kT) - 1$, of spontaneous and stimulated emissions rates. For example, if we have to generate light of 632.8nm ($\nu = 4.74 \times 1014$ Hz) wavelength at room temperature from the system of He–Ne, the ratio of spontaneous and stimulated emission will be almost 5 × 1026, which shows that for getting strong lasing one has to think apart from the thermal equilibrium. For shorter wavelength, laser, ratio of spontaneous to stimulated emission is larger, ensuring that it is more difficult to produce UV light using the principle of stimulated emission compared to the IR. Producing intense laser beam or amplification of light through stimulated emission requires higher rate of stimulated emission than spontaneous emission and self-absorption, which is only possible for N2 >N1 (as B12 = B21) even though E2 >E1 (opposite to the Boltzmann statistics). It means that one will have to create the condition of population inversion by going beyond the thermal equilibrium to increase the process of stimulated emission for getting intense laser light. If a collimated beam of monochromatic light having initial intensity I0 passes through the mentioned active medium, after travelling length x, intensity of the beam is given by I(x) = I0e−αx, where α is the absorption coefficient of the medium, which is proportional to the difference of N1 and N2. In the case of thermal equilibrium N1 _ N2 the irradiance of the beam will decrease with the length of propagation through the medium. However, in the case of population inversion, (N2 >N1) − α, will be positive and the irradiance of the beam will increase exponentially as I(x) = I0ekx, where k is the gain coefficient of the medium and may be given by k = (nNdhν21B21)/c, where Nd is N2−N1, c is speed of light, and n is refractive index of the medium. Laser cutting is a thermal cutting process as shown in Figure 1.1 the principle components includes the lasers power source with some shutter control, beam guidance train, focusing optics and a means of moving the beam or work piece relative to each other. When the beam is required, the shutter mirror is rapidly removed by a solenoid or pneumatic piston. And the beam generated with the laser power source passes to the beam guidance which directs the beam to the focusing optic. The focusing optic can be either transmissive or reflective. The reflective optics consists of parabolic off-axis mirrors. The focused beam then passes through and melts the material throughout the material thickness and a pressurized gas jet. The gas jet is needed both to aid the cutting operation and to protect the optic from spatter.

1.4 Laser Fusion Cutting[14]

In this process, the laser beam heats up the material to melt, using an inert gas such as nitrogen, to blow away the melted material. The inert gas also can help protect the heated material from the surrounding air as well as protecting the laser optics. The process is shown in Figure 1.2.

The energy requirements are lower than in the vaporization cutting. Laser fusion cutting is mainly used for metal material this is also include highly alloyed steels like stainless steel, aluminium and titanium alloys. The advantage of this process is that the cut edge is free of oxides with high quality. The main problem need to be avoided is the adherent melt at the bottom edges of the kerf, especially for cutting thick material This problem can be solved by using high pressure gas jet (above 10 bars).

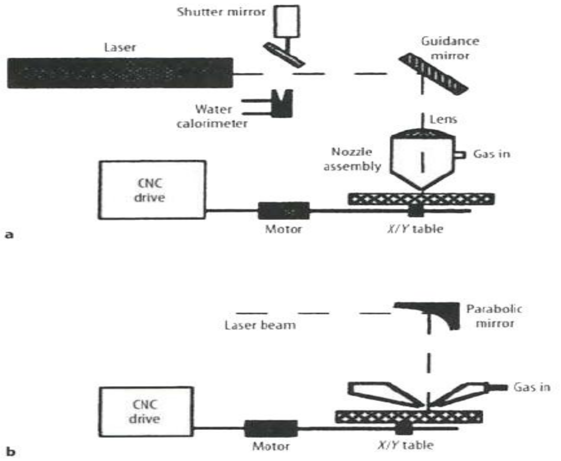

Fig 1.1. General arrangement for laser cutting: a. transmissive optics; b. Reflective optics

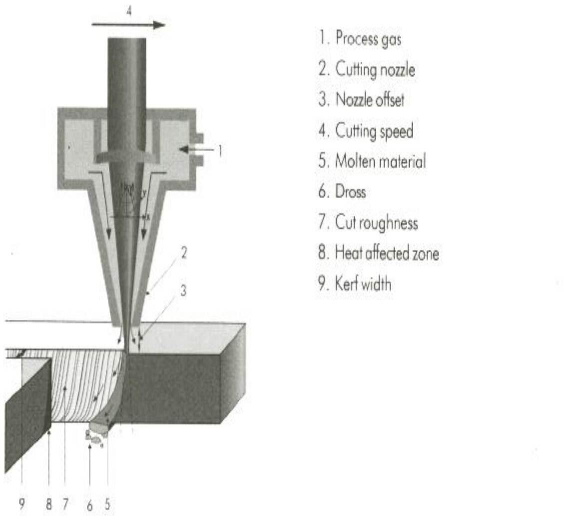

Fig 1.2 .Operating principle of Laser Fusion Cutting

1.5 Laser Oxygen Cutting[14]

In this process, the laser beam heats the material in an oxidizing atmosphere up to the melting point of the material. Therefore an additional source of energy is obtained from the exothermic oxidation reaction of the oxygen with the material. And the molten material is rapidly removed away by the assist gas as shown in Figure 1.3.

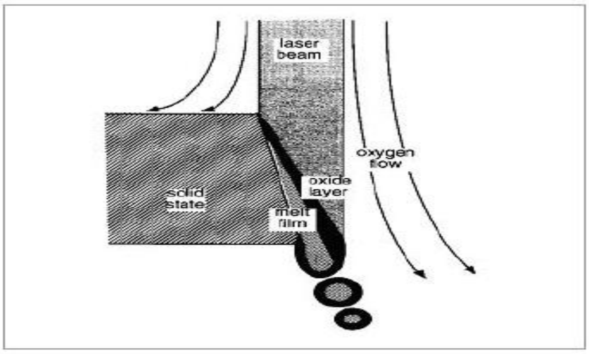

Fig 1.3. Basic Principle of Laser Oxygen Cutting

The laser oxygen cutting is mainly used for steel and low-alloyed steel. Compared to the vaporized cutting method, about one twentieth of the energy is required with a very high processing speed. However, the cut edge is oxidized.

1.6 Laser Vaporization Cutting[14]

In the process of vaporization cutting, the material is heated beyond its melting temperature and eventually evaporated. Therefore, a keyhole is generated in the evaporated position. The keyhole causes a sudden increase in the absorptivity, because of the multiple reflections. And then it results the keyhole deepens rapidly, so vapour is generated and escapes. The process gas can help the material removal. Figure 1.4 is a schematic of laser vaporization cutting.

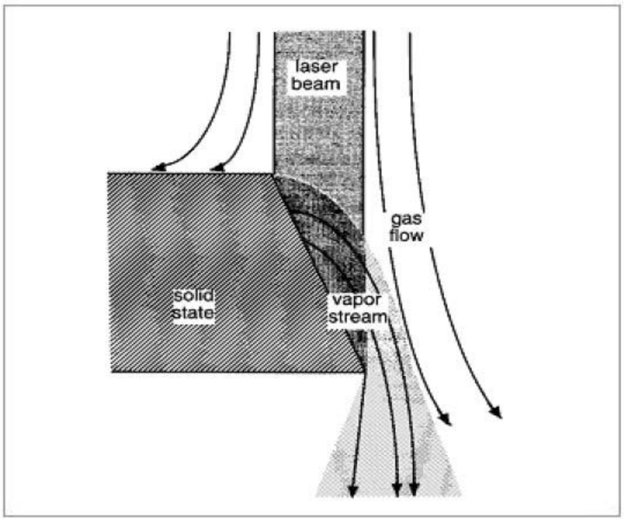

Fig 1.4. Basic principle of Laser Vaporization Cutting

The energy requirements of this process depend upon the thermal properties of the base material, but are usually quite high. This method is usually used to cut material which do not melt such as wood, carbon and some plastic.

1.7 Types of Laser and Their Operations[13]

Depending on the nature of the active media, lasers are classified into three main categories, namely, solid, liquid, and gas. Scientists and researchers have investigated a wide variety of laser materials as active media in each category since 1958, when lasing action was observed in ruby crystal. It is inconvenient to discuss all lasers having these materials as active media.

1.7.1 Solid Laser (Doped Insulator Laser)[13]

Solid state lasers have active media obtained by embedding transition metals (Ti+3, Cr+3, V+2, Co+2, Ni+2, Fe+2, etc.), rare earth ions (Ce+3, Pr+3, Nd+3, Pm+3, Sm+2, Eu+2,+3, Tb+3, Dy+3, Ho+3, Er+3, Yb+3, etc.), and actinides such as U+3 into insulating host lattices. Energy levels of active ions are only responsible for lasing actions, while physical properties such as thermal conductivity and thermal expansivity of the host material are important in determining the efficiency of the laser operation. Arrangement of host atoms around the doped ion modifies its energy levels. Different lasing wavelength in the active media is obtained by doping of different host materials with same active ion. Y3Al5O12, YAlO3, Y3Ga5O12, Y3Fe5O12, YLiF4, Y2SiO5, Y3Sc2Al3O12, Y3Sc2Ga3O12, Ti:Al2O3, MgAl2O4 (spinel), CaY4[SiO4]3O, CaWO4 (Scheelite), Cr:Al2O3, NdP5O4, NdAl3[BO3]4, LiNdP4O12, Nd:LaMgAl11O19, LaMgAl11O19, LiCaAlF6, La3Ga5SiO4, Gd3Sc2Al3O12, Gd3Ga5O12, Na3Ga2Li3F12, Mg2SiO4 (Forsterite), CaF2, Al2 BeO4 (Alexandrite), and so on, are some of the important hosts. Active atom replaces an atom in the host crystal lattice. Nd:YAG is one of the best lasing material and is representative of solid state lasing materials.

1.7.2 Nd:YAG Laser Construction and Operation[13]

The schematic diagram of Nd:YAG laser head as shown in Figure1.5, consists of oscillator section, rear mirror, quarter-wave plate, Pockel cells, polarizer, pump chambers, injection seeder, output coupler, D-Lok monitor, fold mirrors, amplifier section, harmonic generator (HG), temperature controller, dichroic mirrors, and Beam Lock pointing sensor. It may have single or multipump chambers, and each chamber consists of single or multiple flash lamps depending on the power of laser. The laser head end panel contains coolant, output connector, coolant input connector, neutral/ground connector, control cable connector, high-voltage connector, Q-switch input connector, and nitrogen purge input connector. The HGs have potassium di-hydrogen phosphate (KDP) and beta barium borate (BBO) crystals for frequency doubling and tripling, respectively. It can be operated in long pulse and Q-switch modes. Long pulse mode has light pulses of almost 200 μs duration and separated from each other by 2–4 μs.

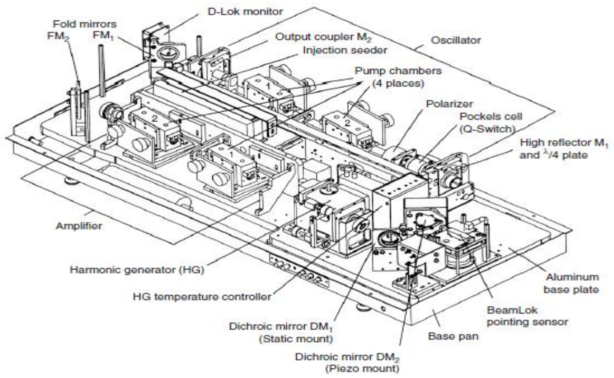

Fig 1.5. Assembly of various components in the head of an Nd:YAG laser system with four pump chambers.

The total energy of the pulse train is similar to that of a single Q-switched pulse. During Q-switched operation, the pulse width is less than 10 ns and the peak optical power is tens of megawatts. The properties of Nd:YAG are the most widely studied and best understood of all solid state laser media. The active medium is triply ionized neodymium, which is optically pumped by a flash lamp whose output matches principle absorption bands in the red and near infrared (NIR). Excited electrons quickly drop to the F3/2 level, the upper level of the lasing transition, where they remain for a relatively longer time (~230 μs). The strongest transition is F3/2 → I11/2, emitting a photon in NIR region (1064 nm). Electrons in the I11/2 state quickly relax to the ground state, which makes its population low. Therefore, it is easy to build up a population inversion for this pair of states with high emission cross section and low lasing threshold at room temperature. There are also some other competing transitions at 1319, 1338, and 946nm from the same upper state, but having lower gain and a higher threshold than the 1064 nm wavelength. In normal operation, these factors and wavelength-selective optics limit oscillation to 1064 nm. A laser comprising just an active medium and resonator will emit a pulse of laser light each time the flash lamp fires. However, the pulse duration will be long, about the same as the flash lamp and its peak power will be low. When a Q-switch is added to the resonator to shorten the pulse, output peak power is raised dramatically. Owing to the long lifetime of F3/2, a large population of excited neodymium ions can build up in the YAG rod in a way similar to which a capacitor stores electrical energy. When oscillation is prevented for some time to build up high level of population inversion by electro-optical Q-switching and after that if the stored energy gets quickly released, the laser will emit a short pulse of high-intensity radiation.

1.7.3 Gas Laser[13]

Gas lasers are widely available in almost all power (milliwatts to megawatts) and wavelengths (UV-IR) and can be operated in pulsed and continuous modes. Based on the nature of active media, there are three types of gas lasers viz atomic, ionic, and molecular. Most of the gas lasers are pumped by electrical discharge.

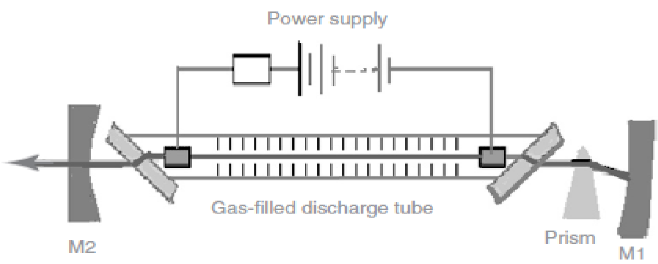

Fig 1.6. Construction of gas laser system (argon ion laser with prism-based wavelength tuning).

Electrons in the discharge tube are accelerated by electric field between the electrodes. These accelerated electrons collide with atoms, ions, or molecules in the active media and induce transition to higher energy levels to achieve the condition of population inversion and stimulated emission. An example of gas laser system is shown in Figure 1.6.

1.7.4 Liquid Laser[13]

Liquids are more homogeneous as compared to solids and have larger density of active atoms as compared to the gasses. In addition to these, they do not offer any fabrication difficulties, offer simple circulation ways for transportation of heat from cavity, and can be easily replaced. Organic dyes such DCM (4-dicyanomethylene- 2-methyl-6-p-dimethylaminostyryl-4H-pyran), rhodamine, styryl, LDS, coumarin, stilbene, LDS, coumarin, stilbene,and so on, dissolved in appropriate solvents act as gain media. When the solution of dye molecules is optically excited by a wavelength of radiation with good absorption coefficient, it emits radiation of longer wavelength, known as fluorescence. The energy difference between absorbed and emitted photons is mostly used by nonradiative transitions and creates heat in the system. The broader fluorescence band in dye/liquid lasers facinates them with the unique feature of wavelength tuning. Organic dye lasers, as tunable and coherent light sources, are becoming increasingly important in spectroscopy, holography, and in biomedical applications. A recent important application of dye lasers involves isotope separation. Here, the laser is used to selectively excite one of several isotopes, thereby inducing the desired isotope to undergo a chemical reaction more readily. The dye molecules have singlet (S0, S1, and S2) and triplet (T1 and T2) group of states with fine energy levels in each of them. Singlet and triplet states correspond to the zero and unit values of total spin momentum of electrons, respectively.

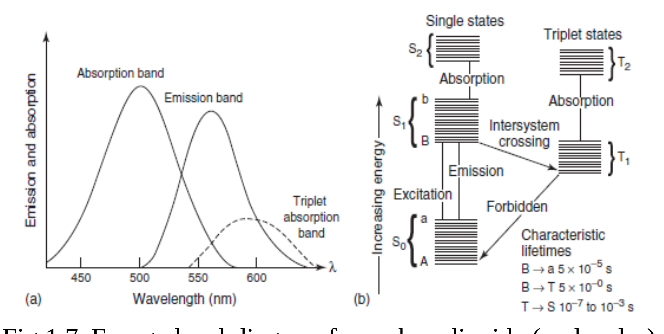

Fig 1.7. Energy level diagram for carbon dioxide (molecular) laser system. Inset shows three mode of vibration of CO_2 molecule

According to selection rules for transitions in quantum mechanics, singlet–triplet and triplet–singlet transitions are quite less probable as compared to the transitions between two singlet or two triplet states. Optical pumping of dye molecules initially at the bottom of S0 state transfers them to the top of S1 state. Collisional relaxation of these molecules takes them to the bottom of S1 state, from where they transit to the top of S0 state with stimulated emission of radiation. Most of the states in the complex systems are usually neither pure singlet nor pure triplet. Singlet states have small contribution of triplet and vice versa. In the case of most of the dye molecules, unfortunately, T1 state lies just below the S1, therefore few molecules transit from S1 to T1 by losing some energy through non radiative transitions. Difference between T1 and T2 states is almost same as the wavelength of lasing transition, therefore emitted lasing radiation gets absorbed, which reduces laser gain and may cease the laser action. Therefore, some of the dye lasers operate in the pulsed mode with the pulse duration shorter than the time required to attain a significant population in the state T1. Some of the dyes also absorb laser radiation corresponding to the transition from S1 to upper singlet transitions. Therefore, one should select the dye molecule so that energy differences between these states do not lie between the ranges of laser radiation.

1.8 Advantages

The advantages of laser cutting are follows:

- Laser cutting machine cut metals with a higher precision than others.
- There is no need for laser metal cutter to contact with the metals, so it won't happen to the metals to become contaminated.
- It's more productive with laser cutting machine. You only need to put the designs into the computer, and they will cut multiple designs in one run.
- The heat affected zone is very less with laser cutting machine.
- Laser cutting is one of the fastest processing that allows metal fabricator to create high quality parts.
- The laser machine uses less energy to cut sheet metal with respect to the technology of plasma cutting.
- This technology can be used to provide a number of materials such as ceramics, wood, rubber, plastics and certain metals are cut.
- Laser cutting is extremely versatile and can be used to cut or burn be simple to complex structures in one piece.
- Because the machine does not require human intervention, except for repairs and inspections, the frequency of accidents and injuries is reduced.

1.9 Disadvantages

- Laser machine will consume much energy, which make it difficult for conventional metal fabricators to join in the metal fabrication system.
- Cutting laser to cut material with a thickness of not

more than 10 mm. The carbon may be up to a thickness of 6to 10 mm and other metals can be cut with a relatively small thickness are cut.

- Production rate is not consistent when laser cutting is used. Will depend largely on the thickness of the work piece, the type of material used and the nature of laser cutting.

1.10 Application field

- Laser cutting is applied for different kinds of materials where complex contours demand precise, fast and force free processing.
- Almost all kinds of metals can be laser cut: mild steel, stainless steel and aluminum are most common application.
- Other laser cut parts are made from wood, plastics, glass and ceramics.
- Medical device and instruments.
- Aerospace and electronics.
- Automotive and micro components
- Jewelry(gold, silver, platinum, titanium)

II. LITERATURE REVIEW

[1] Omer Ozgur Kardas et all carried out Experiment on 2024 aluminum alloy through using laser cutting. They examined Morphological changes and elemental composition in the cut section are incorporating optical and scanning electron microscopy, and energy dispersive spectroscopy. They found that temperature predictions agree well with the experimental data and the differences between both results are negligibly small. Temperature well exceeding the melting temperature of the substrate material occurs, which in turn results in sharp temperature decay around the laser irradiated region. They observed at the kerf exit due to increased viscosity in this region and reduced drag force due to the momentum loss of the assisting as in kerf.[1]

[2] Adrian H.A. Lutey has highlighted the principal factors affecting laser cutting efficiency and quality for LFP battery electrodes. The largely different physical properties of the metallic and active coating layers have been shown to be of large influence on electrode response to laser irradiation. It is clear that the response of thin multi-layer films with layers of largely different physical properties is a combination of a number of inter related factors; however, the principal finding of the present study is that optimization of metallic conductor layer ablation efficiency leads to highest electrode cutting efficiency and quality due to minimization of residual heat deposition in the electrode film. Given the sensitivity of the electrode active layers to heat exposure, optimization of laser cutting parameters for LFP electrodes represents an important step towards effective utilization of laser sources in the EV automotive battery production industry. They were worked on Characterization of process efficiency and quality. They showed that Incision depth is a function of average laser power, with metallic conductor layers being of large influence on the process despite their low thickness compared to the active coating layers. They also found that the Pulsed exposures with shorter pulse durations and higher exposure velocities lead to higher cutting efficiency.[2]

[3] Zhuoru Wu Et all worked on The hybrid CO2-LWJ machining system used for cutting experiments on two different thickness of PCBN blank samples in order to study the effect of processing parameters on the fracture behaviors and to estimate the size of phase transformed zone as well as associated expansion strain. Three different fracture behaviors were observed in cutting experiments on thinner PCBN blanks indicating a transition from scribing to through-cut at threshold value of laser line energy.[3]

[4] Yoshihiro Sagisaka et all carried out worked on Microparts processing using laser cutting. They applied the laser peen forming to the bending of pure titanium thin sheet with a picosecond laser and a femtosecond laser. They have been investigated changes of bending properties with atmosphere and pulse duration. They revealed that femto second laser irradiation in air showed the best bending efficiency. The femtosecond laser is suitable for laser cutting. They proposed a new combined process of laser cutting and laser peen forming with the femtosecond laser.[4]

[5] H.A. Eltawahni et all worked on wood material though using laser cutting. They took input parameter like laser power, cutting speed, air pressure and focal point position. They investigated on the cutting edge quality parameters like upper kerf (UK), lower kerf (LK), the ratio between upper to lower kerfs and the operating cost. They found that the laser power and cutting speed have the main effect on the average lower kerf width and The focal point position and the laser power have the principal role in affecting the ratio. They showed that the upper kerf decreases as the cutting speed and air pressure increase, and it increases as the laser power increases.[5]

[6] Raghavendra Rao et all reported on optimization of Nd:YAG laser cutting of thin superalloy sheet using grey relational analysis with entropy measurement. They determination of the optimum laser cutting process parameters which minimize the kerf width, kerf taper, and kerf deviation together during pulsed Nd:YAG laser cutting of a thin sheet of nickel-based superalloy SUPERNI 718. They took input process parameters considered are oxygen pressure, pulse width, pulse frequency, and cutting speed. They adopted L27 orthogonal array has been used for conducting the experiments for both straight and curved cut profiles. The designed experimental results are used in grey relational analysis and the weights of the quality characteristics are determined by employing the entropy measurement method. They obtained significant parameters performing analysis of variance (ANOVA). They found that the optimal parameter level suggested for straight cut profiles are not valid for curved cut profiles. The application of the hybrid approach for straight cuts has reduced Kt and Kd by 52.37% and 17%, respectively. For curved cuts the approach has reduced Kw and Kt by 8.45% and 44.44%, respectively.[6]

[7] H.A. Eltawahni et all studied to Investigating the CO2 laser cutting parameters of MDF wood composite material with cut three thicknesses 4, 6 and 9 mm. They took various

process factors like laser power, cutting speed, air pressure and focal point position for measured cutting quality in form of the upper kerf width, the lower kerf width, the ratio between the upper kerf width to the lower kerf width, the cut section roughness and the operating cost. The effect of each factor on the quality measures was determined. The average upper kerf width decreases as the focal point position, cutting speed and air pressure increase, and it increases as the laser power increases. The focal point position has the main role in affecting the upper kerf. They also found that the ratio decreases as the focal point position and laser power increase, however, the laser power effect reduces as the material becomes thicker.[7]

[8] Arsalan Qasim et all presented on optimization of process parameters for machining of AISI-1045 steel using Taguchi design and ANOVA. They investigated on various responses such as surface roughness, power consumption, deformed chip shape, and temperature in the workpiece. The effects of varying cutting speed, feed rate, depth of cut, and rake angle in orthogonal cutting process have been considered. The Finite Element (FE) simulations have been carried out with a general purpose commercial FE code, ABAQUS, and statistical calculations have been performed with Minitab. Results show that for optimum cutting forces, feed rate and depth of cut are the most important factors while for lower temperatures, cutting speed and rake angle play a significant role. It is concluded that carbide cutting tools is a better option as compared to uncoated cemented carbide cutting tool for machining AISI 1045 steel as it results in lower cutting forces and temperatures.[8]

[9] Chen-Hao Li et all presented to optimal laser parameters for cutting QFN (Quad Flat No-lead) packages by taguchi’s matrix method. They influenced of the various process parameters such as laser current, laser frequency, and cutting speed on the laser cutting quality. They found that the laser frequency of 2 kHz, the cutting speed of 2 mm/s, and the driving current of 29 A.[9]

[10] Adrian H.A. Lutey et all reported on laser cutting of lithium iron phosphate battery electrodes through characterization of process efficiency and quality. They found that the Incision depth was a piece-wise function of average laser power, with metallic conductor layers being of large influence on the process despite their low thickness compared to the active coating layers. It is clear from results that pulse overlap generally reduces the per-pulse ablation rate. This effect is due to partial screening of the incident beam by the ablation products of previous pulses.[10]

[11] Sohail Akhtar et all investigated on laser cutting of rectangular geometry into aluminium alloy to investigated the effect of cut sizes on thermal stress field. They used thermocouple data to predicted Temperature. To identify the morphological changes in the cutting section, an experiment is carried out and the resulting cutting sections are examined under optical and scanning electron microscopes. they found that temperature and stress fields are affected by the size of the rectangular cut geometry. Temperature and von Mises stress attains higher values for small size rectangular geometry as compared to its counterpart corresponding to the large size geometry. Laser cut sections are free from large size asperities including sideways burning and out-off flatness at the cut edges. They observed locally scattered some small dross attachments at the kerf exit.[11]

[12] Erica Librera et all conducted experiment to compare the two technologies, the quality of the cut-edge for the fusion cutting process of stainless steel (AISI 304) is analyzed. They considered two different cases, 6 mm that is a medium thickness and 10 mm, where due to the high thickness the difficulties of the cutting are more evident. They define a simple and repeatable method to identify the type of cutting process analyzed through the reconstruction of surface characteristics and quality of the cut-edge. As a case study, two stainless steel samples with the same geometry obtained with different laser sources, CO2 and active, fiber was presented. For comparison purposes the cutting conditions were fixed to represent the state of the art of respective laser cutting technologies, which actually show distinct cutting edge characteristics.[12]

2.1 Identified Gaps in The Literature

After a comprehensive study of the existing literature, a number of gaps have been observed in process of Laser cutting technology:

- Most of the researchers have worked on following parameter of Laser cutting process are: 1) Laser Power, 2) Cutting Speed, 3) Air Pressure, and 4) Focal Point etc.
- Literature review present that the researcher have carried out most of the work on optimize process parameter for Reduce heat affected zone, Improving Surface roughness, upper Kerf width, lower Kerf width and Perpendicularity.
- The effect of machining parameter on the work piece are done by the various test are surface roughness test, perpendicularity test, Kerf width measurement test.

2.2 Concluding Remarks

From the literature review I have found that the mostly researcher worked on various material like EN31 steel, AISI1017, AISI4140 steel, S235 mild steel sheets, pure titanium sheets, ceramics and ST52 steel all of they have been worked on Microstructure, Surface Roughness Heat Affected Zone, Temperature and Material Removal Rate. I have been found that very few worked on circularity for circular geometry. I found that very few worked carried out on nickel based INCONEL625 material for measuring Material Removal Rate, Circularity and Heat Affected Zone. Thus, I have decided that the work on INCONEL625 material through laser cutting and I have decided that to work on Circularity, Material Removal Rate and Heat Affected Zone. During visiting of Sun India Company, Odhav,Ahmedabad I came to know that the main variable parameter are Laser Power, Cutting Speed, Gas Pressure, Standoff Distance. So, I have decided that to use above mentioned variable parameter for optimize the Circularity, Material Removal Rate and Heat Affected Zone through

using minitab software. After discussion with the worker and production engineer they are facing problem like higher Surface Roughness of machined surface, lower Material Removal Rate, and high Heat Affected Zone. Laser cutting process is precise cut with small Heat Affected Zone (HAZ). Precision laser cutting involving various materials is important in high-volume manufacturing processes to minimize operational cost, error reduction and improve product quality. In laser cutting operation Laser Power, Cutting Speed, Air Pressure, Focal Points are influencing parameters. To achieve higher accuracy of processing, better quality, smaller width of cut, reduced deformation of material need to study Laser machining process, parametric effects and establish the relationship between the process parameters and the edge quality parameters, Numerical optimization perform to find out optimal process setting.
They also confused about following problem.

- What is primary input power when cutting process?
- How thick is the metal want to cut?
- Traditional way of cutting takes a lot of time.
- The most important factors that influence the cutting process?
- What type of material is to cutting?
- What are the best conditions to achieve optimum performances?

2.3 Input Parameter

- Laser Power
- Cutting Speed
- Gas Pressure
- Standoff Distance

2.4 Output Parameter

- Circularity
- Material Removal Rate and
- Heat Affected Zone

2.5 Objective of Work

- To study laser machining process and select appropriate process parameters for laser cutting.
- Select appropriate design of experiment (Taguchi method) and generate orthogonal array.
- To conducted experiment on laser cutting machine by varying combination of input process parameters.
- To identify the effective process parameters for each responses.
- To optimize the process parameters of laser cutting process.

III. WORK SETUP OR EXPERIMENTAL METHODOLOGY

I will able to work on solid state Nd:YAG Laser cutting machine at Sun India Company,Odhav,Ahmedabad. I will experiments on the Superalloy INCONEL 625 (340×340×10) mm size of plate by the following way:

- First of loading the INCONEL625 on work table.
- Then we need to start power supply to the machine.
- So the chiller unit, laser source and control panel are on.
- Set the reference of cutting sheet by CNC controller with movement of the cutting head.
- Then by the use of laser net software the laser supply is on and simultaneously gas supply is on.
- Then Laser power, gas pressure and cutting speed is control by CNC controller.
- Then setting up cutting head position using CNC controller.
- Using CNC controller I will fix the parameters as per our design of experiments.
- During the machining process for safety purpose we need to wear the hand glows as well as goggles.
- Then I will start cutting process of our material.

3.1 Selection of Machine
For this experiment the whole work can be done by laser cutting. The laser cutting machine, it consists of a Dc power unit, assist gas unit, a mother board for the cutting machine, a computer, a control panel display and the x- y motion assembly. The Dc power supply provides the power for all the sub units. The assist gas unit provides pure assist gas which is used to remove the debris generated during the cutting process. The focusing of the beam on the work is done with the help of solid state Nd:YAG laser.

Fig 3.1. Solid state Nd:YAG Laser

Table 3.1. Specification of Laser cutting (Solid state Nd:YAG Laser)

Max. axis speed	85 m/min
Length	9300 mm
Laser power	2500 watt
Control	Fanuc FS 160
Running hours of laser	14.50 h
Total power requirement	25 KW
Weight approx.	3300 kg
Dimensions approx.	2860 X 2160 X 2150 mm
Traversing range X/Y/Z	1260/1260/100 mm

3.2 Work piece material- INCONEL 625
It is a Non-magnetic Nickel-Chromium-Molybdenum Nickel-based Superalloy strengthened mainly by solid solution hardening effect of the refractory metals, niobium and molybdenum in an austenitic FCC γ matrix. It is known for its high temperature strength and excellent corrosion resistance in a wide range of corrosive media, being

especially resistant to crevice and pitting corrosion. It maintains its mechanical strength and toughness in the temperature range.

The presence of molybdenum (8-10%wt.) is good for resistance against crevice and pitting corrosion. Niobium stabilises the alloy against sensitisation during welding making it the choice for many diverse applications.

The alloy is highly resistant to chloride-stress corrosion cracking and oxidation at high temperature. The high ductility of Inconel 625 is responsible for its ability to withstand solidification and contraction after welding thereby reducing the possibility of cracking Inconel 625 alloy is a material of choice for gas turbine engine ducting, combustion liners, furnace hardware, spray bars and special seawater applications in aerospace, chemical, petrochemical and marine industries.

Fig 3.2. Work piece material INCONEL 625

3.2.1Chemical Composition

Table 3.2. Chemical Composition

Ni	Cr	Mo	Nb+Ta	Fe	C	Mn	Si	P	S	Al	Ti	Co
58.0% min	20.0 to 23.0%	8.0 to 10.0 %	3.15 to 4.15%	5.0% max	0.1% max	0.5% max	0.5% max	0.015 % max	0.015 % max	0.4% max	0.4% max	1.0% max

3.2.2Mechanical Properties

Table 3.3. Mechanical Properties

Density	8.44 g/cm3
Melting point	13500c
Coefficient of expansion	12.8 µm/m0c
Modulus of rigidity	79 KN/mm2
Modulus of elasticity	205.8 KN/mm2

3.3 Performance Evaluation Criteria

- Material Removal Rate (MRR)
- Circularity
- Heat Affected Zone(HAZ)

3.3.1Material Removal Rate

The material Removal Rate, MRR, can be defined as the volume of material removed divided by the machining time. Material Removal Rate (MRR) is defined by :

$MRR = (W_i – Wf) / (\rho_w T)$

Where,

Wi = initial weight of work piece (g)

Wf = final weight of work piece material (g)

T = cutting time(s)

ρ_w = Work piece density (g/ mm^3)

Fig 3.3. Digital weight balancer(Courtesy: Sun India Company)

The weight of the work piece before and after the cutting process need to be measure to obtain MRR.

Specification of the Digital weight Balancer:

Table 3.4. Specification of the Digital weight balancer

Capacity	100 kg
Accuracy/readability	5 gm
Platform size	42.5 cm X 42.5 cm

3.3.2 Circularity

It is one of the most important parameter to check hole quality performance. It is defined as a two dimensional geometric tolerance that controls how much a feature can deviate from a perfect circle. Measurement of circularity is done by Co-ordinate measuring machine (CMM) IGTR, vatva, ahmedabad. Dimensional accuracy measured by Coordinate Measurement Machine (CMM)Mitutoyo BRM 5071. CMM is an advanced, multi-purpose quality control system used to help inspection keep pace with modern production requirements. It replaces long, complex and inefficient conventional inspection methods with simple procedures. A CMM provides instant measurement results without complicated setup and operating procedures. It combines surface plate, micrometer and vernier type inspection methods into one easy to use machine. CMM can check the dimensional and geometric accuracy of everything from small engine blocks, to sheet metal parts, to circuit boards. A CMM consists essentially of a probe supported on three mutually perpendicular (X, Y & Z) axes. Each axis has a built-in reference standard.

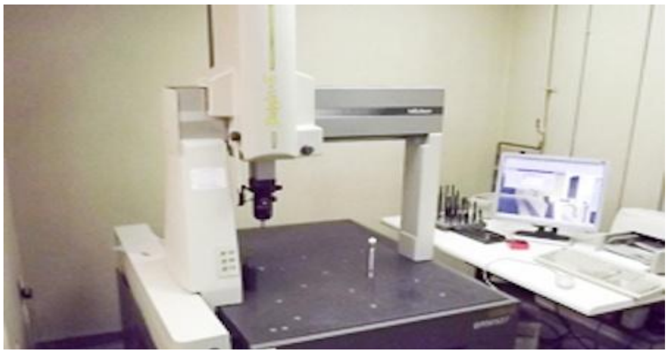

Fig 3.4. coordinate Measuring Machine(Courtesy: IGTR,Vatva,Ahmedabad)

Procedure for simple measurements on a CMM includes:

- Calibration of the probe system.
- Define datum(s) on the work piece.
- Perform measurement(s).
- Compute the required dimensions from measurements made in Step 3. Assess conformance to specification.

Technical specifications

Table 3.5. Technical specifications

X-Y-Z	20”x28”x16”
Resolution	000020”
Floor Space	56” X 47” X 89”
Weight	1424 Lbs
Completer with cosmo software version 1.4	
PH2 touch probe with stylus, monitor, printer, clamping hardware and compresses air cleaner filter	

3.3.3 Heat Affected Zone

Cutting processes that use intense heat, like oxyfuel cutting and plasma arc cutting, produce thermal effects near the edge of the cut that lead to microstructural and metallurgical changes in the metal. The portion of a metal work-piece that has been so altered by heat is termed the “Heat-Affected Zone” or HAZ. All thermal cutting processes create an HAZ in the cut metal. The changes induced by heat can include:

- Altering the microstructure of particular steels, leading to an increase in the hardness of the cut edge relative to the un-cut metal.
- Altering the microstructure of particular steels, leading to a decrease in the strength of the cut edge.
- The formation of nitrides on the cut edge, which can affect the weldability of the cut face.
- Distortion of the metal being cut. Some changes, such as heat-tint, are cosmetic and do not matter in some applications. For other applications, discoloration may matter a great deal.

The width of the heat-tint is influenced by the surface condition of the metal. Any surface contaminant or coating, such as paint, oxidation, oil, and even fingerprints, will affect the formation of heat-tint. HAZ width is influenced only by the thermal history of the metal. While the change in the coloration of the metal may by chance approximate the width of the heat- affected zone, heat-tint width can be either larger or smaller than the HAZ. It is important to remember that the HAZ is inside the metal and you cannot see it. Other changes to the metal, like warping or hardening, affect weldability and usefulness of the metal after the cut. The heat affected zone may need to be partially or totally removed before the metal part can be used.

The width of the HAZ is influenced by:

- Cut speed – in general, faster speeds result in a smaller HAZ.
- Amperage (when using plasma) – for a given thickness of metal, a higher amperage (and consequently a faster cut speed) results in a smaller HAZ.

The type of metal being cut different metals transfer heat at different rates and respond to differently to elevated temperatures. Increased temperatures and longer cutting times will result in a wider HAZ. As an example, a Plasma arc cutter can be used to cut any electrically-conductive material, but all things being equal it will create a different width HAZ on aluminium than on mild steel of the same thickness.

Another thing to note about the HAZ is that when cutting thicker metals the width of the zone may be smaller at the top of the cut edge and wider at the bottom.

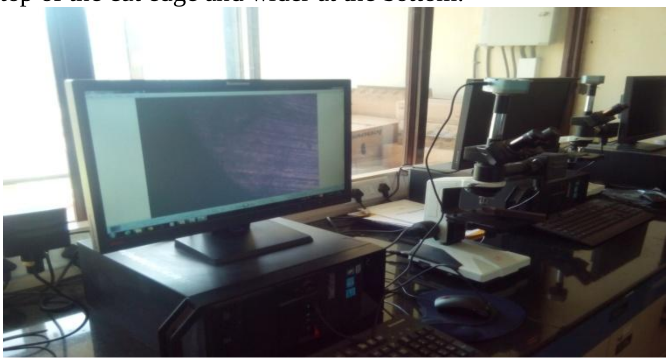

Fig 3.5.Optical Microscope(Courtesy: Cipet ,ahmedabad)

Specification of the Optical Microscope

Fully usable 14" (355mm) viewing screen with edge-to-edge accuracy of 0.05%, 15.5" (394mm) glass screen.

- 8" X axis (203mm) and 4" Yaxis (101.1 mm) stage.
- Hard anodized stage surface.
- Screen-locking mechanism.
- Digital Electronic Screen Protractor with INC/ABS switchable displays 1'or .010.
- Quick-change 3 Position Lens Turret.
- Vertical screen for easy viewing.
- Rotating Chart Clip System mounted on screen.
- Quick-release X axis clutch for rapid stage movement with infinite fine adjustment.
- Telocentric Lens System.
- 150 watt Profile Illumination System with high/low intensities.

3.4 Design of Experiment

Design of the experiments can be used to systematically investigate the process or product variables that influence product quality and quantity. DOE is a series of tests in which purposeful changes are made to the input variables of a system, process and the effect on response parameters and variables are measured. Design of experiments is applicable to both physical processes and computer models. After identify the process conditions and product components that influence product quality or quantity, you can direct improvement efforts to enhance a products mfg, reliability, quality, quantity and field performance.

Experimental design is an effective for maximize the amount of information gained from a study while minimize the amount of data to be collected. In the highly competitive world of testing or evaluation, an efficient method for testing many factors is needed.

The advantages of design of experiments are as follows:

- Numbers of trials is significantly reduced.
- Qualitative estimation of parameters can be made.
- Experimental error can be estimated.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Inference regarding the effect of parameters on the characteristics of the process can be made.
- Optimal setting of the parameters can be found out.

3.4.1 Taguchi Design of Experiment

The general steps involved in the Taguchi Method are as follows:

- Define the process objective, a target value for a performance measure of the process. The target of a process may also be a minimum or maximum.
- Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as gas pressure, current flow rate, cutting speed and arc gap etc. that can be easily controlled. The number of levels of the parameters should be specified. Increasing the number of levels to a parameter at increases the number of experiments to be conducted.
- Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays will be discussed in considerably more detail.
- Conducted the experiments indicate in the completed array to collect the data on the effect on the performance measure.
- To determine the data analysis effect of the different parameters on the performance measure.

The number of parameters and the number of levels, the proper orthogonal array can be selected. Using the array selector table and the name of the appropriate array can be found by looking at the column and row corresponding to the number of parameters and number of levels.

These arrays were created using an algorithm Taguchi developed. Links are provided to many of the predefined arrays given in the array selector table and allows for each variable and setting to be tested equally.

Once the parameters affecting a process that can be controlled. The levels at which these parameters should be varied must be determined and determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum and current value of the parameter.

The effect of different parameters on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design proposed by Taguchi.

To determine the effect each variable has on the output then the signal-to-noise ratio needs to be calculated for each experiment conducted.

For maximizing the performance characteristic, the following definition of the signal to noise ratio should be calculated.

$$\frac{S}{N}\ ratio = -log_{10}\,({}^{1}/_{n})\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}}$$

For minimizing the performance characteristic, the following definition of the S/N ratio should be calculated:

$$S/N\ ratio = \ -log_{10}\,(\frac{1}{n}\sum_{j=1}^{n}y_{ij}^{2})$$

Where, n = number of replications

y_{ij} = observed response value, Where, i= 1,2,…..; j=1,2,…k

There are four parameters and Five levels, the orthogonal array L25 can be selected.

3.5 Process Parameters

3.5.1 Gas Pressure[15]

Nitrogen gas is the preferred gas for the cutting of stainless steel, high-alloyed steel. When high-pressure nitrogen cutting is used to cut stainless steel, it produces a bright, oxide free cut edge but the processing speeds are lower than in oxygen assisted cutting.Burr-free cutting conditions are achieved by optimization of the principle processing parameters; nozzle diameter, focal position and gas pressure.Oxygen is normally used for cutting of mild steel and low-alloyed steels. Use of oxygen causes an exothermic reaction, which contributes to the cutting energy resulting into high cutting speeds and the ability to cut thick sections up to 12mm.oxygen cutting leads to oxidized cut edges and requires careful control of process parameters to minimize dross adherence and edge roughness.The oxygen pressure is reduced as plate thickness is increased to avoid burning effects and the nozzle diameter is increased.The nitrogen pressure lies in the range of 10-20 bar and the pressure requirement increases with increasing material thickness. The high gas pressure provides an extra mechanical force to blow out the molten material from the cut kerf.

3.5.2 Nozzle Diameter and Standoff Distance[15]

The nozzle delivers the cutting gas to the cutting front ensuring that the gas is coaxial with the laser beam and stabilizes the pressure on the work piece surface to minimize turbulence in the melt pool. The nozzle design, particularly the design of the orifice, determines the shape of the cutting gas jet and hence the quality of the cut.The stand-off distance is the distance between the nozzle and the workpiece.This distance influences the flow patterns in the gas, which have a direct bearing on the cutting performance and cut quality.A Stand-off distance smaller than the nozzle diameter is recommended because larger standoff distances result in turbulence and large pressure changes in the gap between the nozzle and work piece.

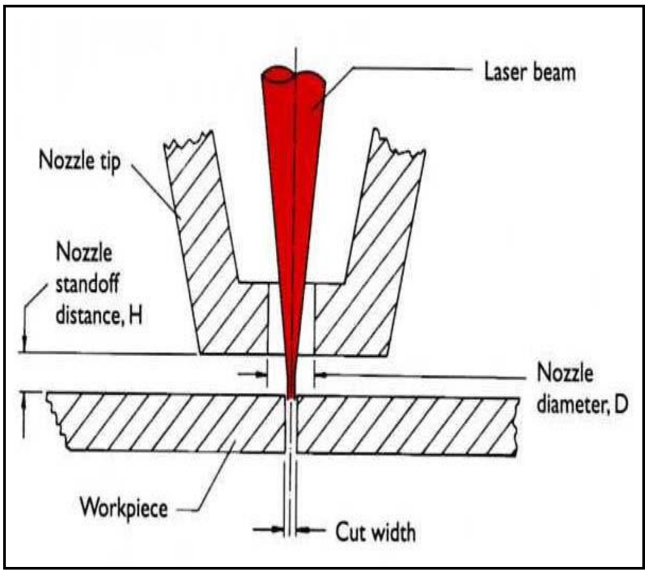

Fig 3.6.Nozzle Diameter

3.5.3 Nozzle Alignment[15]

Nozzle misalignment may cause poor cutting quality, as the process is extremely susceptible to any discrepancy in the alignment of the cutting gas jet with the laser beam. The gas flow from the nozzle generates a pressure gradient on the material surface, which is coaxial with the nozzle itself. If the nozzle and the focused laser beam are coaxial then there will be uniform lateral gas flow. Nozzle-laser beam misalignment leads to an overall directional gas flow across the top of the cut zone which can lead to unwanted cut edge burning and dross adhesion.

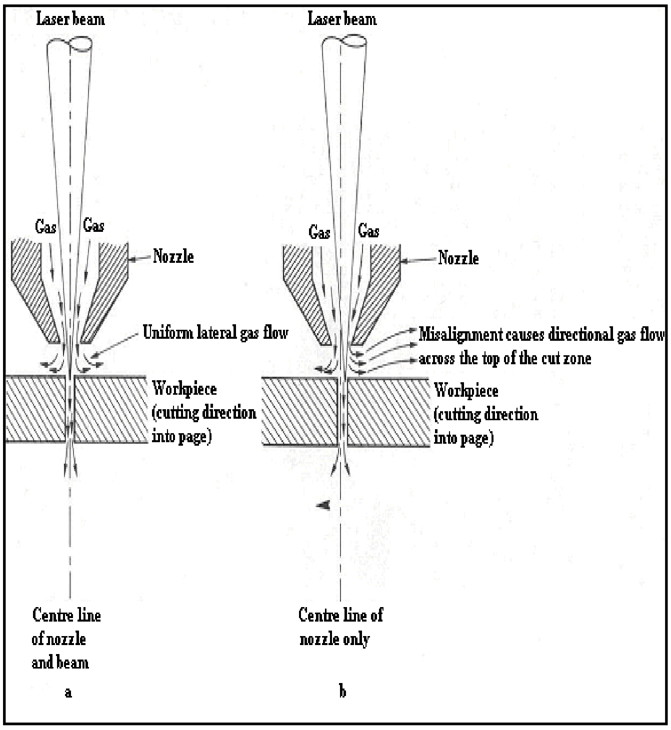

Fig 3.7. Nozzle Alignment

3.5.4 Laser Power[15]

Laser power is the total energy emitted in the form of laser light per second while the intensity of the laser beam is the power divided by the area over which the power is concentrated. Reflectivity of most metals is high at low beam intensities but much lower at high intensities and cutting of thicker materials requires higher intensities. The optimum incident power is established during procedure development because excessive power results in a wide kerf width. The optimum incident power is established during procedure development because excessive power results in a wide kerf width, a thicker recast later and an increase in dross while insufficient power cannot initiate cutting.

3.5.6 Cutting Speed[15]

The energy used in cutting is independent of the time taken to carry out the cut but the energy losses from the cut zone are proportion to the time taken. The energy lost from the cut zone decreases with increasing cutting speed resulting into an increase in the efficiency of the cutting process. A reduction in cutting speed when cutting thicker materials leads to an increase in the wasted energy and the process becomes less efficient. The cutting speed must be balanced with the gas flow rate and the power. As cutting speed increases, striations on the cut edge become more prominent, dross is more likely to remain on the underside and penetration is lost. The speed must be reduced when cutting sharp corners with a corresponding reduction in beam power to avoid burning.

Range of Process Parameters

Table 3.6. Range of Process Parameters

Parameter	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Laser Power	Watt	150	200	250	300	350
Cutting Speed	mm/min	1200	1500	1800	2100	2400
Gas Pressure	Bar	2	3	4	5	6
Standoff Distance	mm	0.5	0.8	1	1.2	1.5

Fixed Process Parameters

Table 3.7. Fixed Process Parameters

Frequency (Hz)	1550
Nozzle Gap (mm)	1.5
Nozzle Diameter (mm)	1.5
Focus Setting (mm)	125

Taguchi L25 Orthogonal Array

Table 3.8. Taguchi L25 Orthogonal Array

SR. NO.	LASER POWER [W]	CUTTING SPEED [mm/min]	GAS PRESSURE [Bar]	STANDOFF DISTANCE [mm]	MRR [mm^3/ min]	CIRCULARITY [mm]	HAZ [mm]
1	150	1200	2	0.5			
2	150	1500	3	0.8			
3	150	1800	4	1.0			
4	150	2100	5	1.2			
5	150	2400	6	1.5			
6	200	1200	3	1.0			
7	200	1500	4	1.2			
8	200	1800	5	1.5			
9	200	2100	6	0.5			
10	200	2400	2	0.8			
11	250	1200	4	1.5			
12	250	1500	5	0.5			
13	250	1800	6	0.8			
14	250	2100	2	1.0			
15	250	2400	3	1.2			
16	300	1200	5	0.8			
17	300	1500	6	1.0			
18	300	1800	2	1.2			
19	300	2100	3	1.5			
20	300	2400	4	0.5			
21	350	1200	6	1.2			
22	350	1500	2	1.5			
23	350	1800	3	0.5			
24	350	2100	4	0.8			
25	350	2400	5	1.0			

3.6 Regression Model

The regression model for predicting the response parameters in cutting can be derived using methods like regression analysis.

Regression analysis is often used to:

- Determine how the response variable changes as particular predictor variable changes.
- Predict the value of the response variable for any value of the predictor variable, or combination of values of the predictor variables.

Regression is method of estimating the conditional expected value of one variable, y, given the values of some other variable, x. The variable of interest, y, is called the dependent variable. The other variable, x, is called the independent variable.

Regression analysis is a statistical tool for the investigation of relationships between variables. Usually, the investigator seeks to ascertain the casual effect of one variable upon another, for example, the effect of changes in cutting speed, feed and depth of cut on cutting forces. To explore such issue, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the casual variables upon the variable that they influence. The investigator also typically assesses the ―statistical significance‖ of the estimated relationships, that is, the degree of confidence that the true relationship is close to the estimated relationship. The regression equation is an algebraic representation of the regression line and is used to describe the relationship between the response and predictor variables. The regression equation takes the form of:

Response= constant + coefficient (predictor) +… + coefficient (predictor) OR Y= b0 + b1x1+b2x2+…+bkx

Where;

- Response (Y) is the value of the response.
- Constant (b0) is the value of the response variable when the predictor variable(s) is zero. The constant is also called the intercept because it determines where the regression line intercepts (meets) the Y-axis.
- Predictor (X) is the value of the predictor variable.

Coefficients (b1, b2… bk) represent the estimated change in mean response for each unit change in predictor value. In other words, it is the change in Y that occurs when X increase by one unit. The mathematical model using regression analysis is derived with the help of MINITAB software.

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